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Geomagnetic control of the *f*oF2 long-term trends

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Abstract. Further development of the method proposed by Danilov and Mikhailov is presented. The method is applied to reveal the *f*oF2 long-term trends on 30 Northern Hemisphere ionosonde stations. Most of them show significant *f*oF2 trends. A pronounced dependence of trend magnitude on geomagnetic (invariant) latitude is confirmed. Periods of negative/positive *f*oF2 trends corresponding to the periods of long-term increasing/decreasing geomagnetic activity are revealed for the first time. Pronounced diurnal variations of the *f*oF2 trend magnitude are found. Strong positive *f*oF2 trends in the post-midnight-early-morning LT sector and strong negative trends during daytime hours are found on the sub-auroral stations for the period with increasing geomagnetic activity. On the contrary middle and lower latitude stations demonstrate negative trends in the early-morning LT sector and small negative or positive trends during daytime hours for the same period. All the morphological features revealed of the *f*oF2 trends may be explained in the framework of contemporary F2-region storm mechanisms. This newly proposed F2-layer geomagnetic storm concept casts serious doubts on the hypothesis relating the F2-layer parameter long-term trends to the thermosphere cooling due to the greenhouse effect.

Key words: Ionosphere (ionosphere-atmosphere interactions; ionospheric disturbances)

1 Introduction

Long-term variations (trends) of the upper atmosphere and ionosphere parameters are widely discussed in recent publications due to the problem of global climate changes (see reviews by Danilov, 1997, 1998; Givishvili and Leshchenko, 1994, 1995; Givishvili *et al.*, 1995; Ulich and Turunen, 1997; Rishbeth, 1997; Danilov and Mikhailov, 1998, 1999; Bremer, 1992, 1998; Upadhyay and Mahajan, 1998). After the model calculations of Rishbeth (1990) and Rishbeth and Roble (1992) predicting the ionospheric effects of atmospheric greenhouse gas concentration increase, the researchers have been trying to relate the observed long-term trends in the ionospheric parameters to this greenhouse effect (Bremer, 1992; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997, Jarvis *et al.*, 1998; Upadhyay and Mahajan, 1998). However an analysis has shown that the worldwide pattern of the F2 and E-layer parameter long-term trends is very complicated and cannot be explained sufficiently by this effect. Further analysis by Bremer (1998) of many European ionosonde stations and by Upadhyay and Mahajan (1998) of a global set of ionosonde stations has shown that the F2-layer parameter trends turn out to be different both in sign and magnitude for different stations and this cannot be reconciled with the greenhouse hypothesis. A contradiction with this hypothesis was revealed also by Givishvili and Leshchenko (1996, 1998) when analyzing the *f*oE long-term trends. They found that observed *f*oE trends may be related to the long-term variations in molecular oxygen abundance in the lower thermosphere. Therefore, the physical mechanism of the observed ionospheric trends remains unclear.

Danilov and Mikhailov (1998) proposed a new approach to reveal *f*oF2 trends. When referring to *f*oF2 trends we mean linear trends everywhere. With this new approach they obtained negative trends for all 22 ionospheric stations considered and a pronounced dependence of the trend magnitude on geomagnetic latitude. This was the first indication that F2-layer trends might be related to the long-term changes in geomagnetic activity. Further analysis of the *f*oF2 trends is performed here to check this geomagnetic hypothesis.

2 The method and data

The method used for *f*oF2 trend analysis is described by Danilov and Mikhailov (1999), but as it is being

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improved, the main points of the method are given. It should be stressed that different authors use different approaches to extract long-term trends from the ionospheric observations and the success of analysis depends to a great extent on the method used. The useful "signal" is very small and the "background" is very noisy, so special methods are required to reveal a significant trend in the observed *f*oF2 variations.

1. Relative deviations of the observed *f*oF2 values from some model

$$\delta f\mathrm{oF2} = (f\mathrm{oF2}_{\mathrm{obs}} - f\mathrm{oF2}_{\mathrm{mod}})/f\mathrm{oF2}_{\mathrm{mod}} \quad (1)$$

are analyzed rather than absolute values considered by Givishvily and Leshchenko (1994, 1995), Bremer (1998) and Upadhyay and Mahajan (1998). The advantage of using relative values instead of absolute ones are discussed by Danilov and Mikhailov (1998).

2. A regression of *f*oF2 with the sunspot number R_{12} (third-degree polynomial) is used as a model. Dependence on monthly *Ap* index was also added to this regression to try exclude the geomagnetic activity effects as was used in some papers (Bremer, 1992, 1998; Jarvis *et al*., 1998), but this does not change the main results (see later).

3. A 12-month running mean hourly *f*oF2 rather than just monthly hourly values are used for the analysis. This is a very important point not used by other researchers, which helps us in revealing long-term trends as it strongly decreases the scatter in observed *f*oF2 data.

4. It was shown in our previous analysis (Danilov and Mikhailov, 1998, 1999) that only by selecting years around solar maxima and minima is it possible to obtain stable significant trends, whereas for all years (including rising and falling phases of solar cycles) there is a chaos with various signs of the trends obtained at various stations (e.g. Bremer, 1998; Upadhyay and Mahajan, 1998). This approach is used in the present study as well, but it is shown that the inclusion of years around solar maximum also contaminates the picture of trends and better results may be obtained using the years around solar minimum only. Therefore, both year selections are used in the present study for a comparison. The chosen years of solar maximum and minimum are shown in Table 1. This selection of years differs to some extent from the $M(3)+m(3)$ selection used in our previous analysis (Danilov and Mikhailov, 1998, 1999). The present one is based on the observed annual mean R_{12} variations. Two to three years around solar cycle extrema with close annual mean R_{12} values are selected for each solar cycle (Table 1). These years represent real solar cycle extrema as the annual R_{12} are seen to differ from the neighbouring R_{12} values belonging to the falling or rising phases of solar cycle.

5. Trends at different stations may be compared if only one precise time period is analyzed. A period 1965–1991, which is the richest in observations over the worldwide ionosonde network was chosen for the main analysis. Observations at most of the selected stations (Table 2) overlap this 1965–1991 time interval. At some stations observations are available for earlier years and they were analyzed separately. On the other hand it should be stressed that the model (*f*oF2 versus R_{12} or R_{12} + *Ap* regression) is derived over all years with *f*oF2 observations available on a particular ionosonde station.

Table 1. Years of solar minimum (*m*) and maximum (*M*) used in the analysis

Years	Annual mean R_{12}	Years	Annual mean R_{12}	Years	Annual mean R_{12}
1930	38.8	1951	64.9	1972	66.8
1931	21.1	1952	32.9	1973	39.0
1932	12.1	1953	14.9 *m*	1974	32.2
1933	5.9 *m*	1954	6.4	1975	17.4 *m*
1934	9.4	1955	41.5	1976	13.4
1935	36.6	1956	133.8	1977	31.9
1936	79.6	1957	187.9 *M*	1978	91.4
1937	113.2 *M*	1958	189.5	1979	148.6
1938	106.4	1959	157.5	1980	154.2 *M*
1939	89.8	1960	108.0	1981	141.3
1940	66.4	1961	59.4	1982	114.3
1941	50.5	1962	36.6	1983	74.7
1942	30.4	1963	27.3	1984	42.2
1943	15.3 *m*	1964	12.3 *m*	1985	17.9 *m*
1944	11.1	1965	16.3	1986	13.8
1945	36.4	1966	49.7	1987	32.1
1946	91.7	1967	89.7	1988	98.5
1947	145.6 *M*	1968	106.6	1989	153.9
1948	141.2	1969	106.5 *M*	1990	145.5 *M*
1949	129.6	1970	100.4	1991	144.0
1950	88.7	1971	69.7	1992	93.8

6. Gaps in the initial observational data are filled in using monthly median values from the MQMF2 model by Mikhailov *et al*. (1996) based on a new ionospheric index MF2 (Mikhailov and Mikhailov, 1995). This monthly median *f*oF2 model was shown to demonstrate the greatest accuracy among the models compared and was accepted as a final result of the COST-251 project (COST 251, 1999). Filling in gaps is necessary to find 12-month running mean *f*oF2 values used in the analysis. All *f*oF2 observations (given in zonal or UT time) were converted to solar local time (SLT) using spline-interpolation.

7. To analyze *f*oF2 trends one should exclude as much as possible the dependence on solar and geomagnetic activity. Thus, we have used two models, a regression of *f*oF2 with R_{12} (model 1) and with R_{12} + monthly *Ap* (model 2) although we realize that both indices poorly represent the *f*oF2 dependence on solar and geomagnetic activity (e.g. Mikhailov, 1999; Prölss, 1983) We discuss this issue later.

8. The test of the significance of the linear trend parameter *K* (the slope) is made with Fisher's *F* criterion (Pollard, 1977)

$$F = r^2(N-2)/(1-r^2) \quad (2)$$

where *r* is the correlation coefficient between δfoF2 and year after Eq. (1), and *N* is the number of pairs considered. Although we are aware of the seasonal variations in trends (Danilov and Mikhailov, 1999), the later analysis has shown that diurnal variations may be much stronger than seasonal ones. Therefore, we have analyzed annual mean trends for a selected LT hours.

Table 2. Ionosonde stations and calculated annual mean slope K (in 10^{-4} per year) for the period after 1965. Regressions *f*oF2 with R_{12} (model 1) and with $R_{12} + Ap$ (model 2) are used to make *f*oF2 trends. Bold face figures show significant trends with a confidence level ≥90%, normal face figures are trends which are not significant at the 90% confidence level

Station	Φ deg	Φ_{inv} deg	Geographic		12 SLT K (M1)	00 SLT K (M1)	12 SLT K (M2)	00 SLT K (M2)
			Lat	Lon				
Kheysa	71.28	74.57	80.60	58.00	**−29.5**	**−29.5**	**−22.2**	**−21.8**
Sodankyla	63.73	63.59	67.40	26.60	**−67.5**	**−39.5**	**−56.0**	**−37.5**
Dikson	62.97	67.61	73.50	80.40	**−21.3**	**−15.8**	**−14.7**	−9.2
Lycksele	62.70	61.46	64.70	18.80	**−26.0**	**+1.9**	**−17.9**	+2.5
Uppsala	58.44	56.61	59.80	17.60	**−27.6**	**−42.5**	**−22.4**	**−29.9**
Salekhard	57.30	61.18	66.50	66.70	**−22.5**	**+23.9**	**−16.4**	**+20.0**
Ottawa	56.78	57.71	45.40	284.10	**−17.7**	**+0.74**	**−12.5**	+9.9
St. Petersburg	56.17	55.91	60.00	30.70	**−16.1**	−19.2	−10.9	**−9.4**
Juliusruh	54.40	51.61	54.60	13.40	**−12.2**	**−33.7**	**−9.0**	**−24.8**
Slough	54.25	49.80	51.50	359.43	−5.9	−13.1	−2.6	−5.9
Kaliningrad	53.10	51.17	54.60	13.40	−10.8	**−27.9**	−8.1	−17.1
Dourbes	51.89	47.80	50.10	4.60	+1.7	**−3.9**	**+3.2**	**+4.0**
Yakutsk	51.00	55.08	62.00	129.60	**−25.8**	**−33.0**	**−19.8**	**−22.1**
Moscow	50.82	51.06	55.50	37.30	−12.0	**−25.6**	−8.7	−16.6
Gorky	50.29	51.43	56.15	44.28	−10.7	−18.8	−8.1	−13.1
Poitiers	49.40	45.05	46.60	0.30	**−0.3**	−9.4	**−0.4**	−6.1
Boulder	48.89	48.80	40.00	254.70	−8.4	+5.0	−6.5	+5.6
Ekaterinburg	48.42	51.45	56.70	61.10	**−12.0**	**−30.2**	−9.5	−23.9
Kiev	47.50	46.48	50.72	30.30	−4.7	−11.5	−4.1	−5.8
Tomsk	45.92	50.58	56.50	84.90	**+5.0**	−16.9	**+6.0**	−12.4
Rome	42.46	37.48	41.90	12.52	**+6.2**	**−2.3**	**+3.5**	**−3.8**
Irkutsk	41.06	45.65	52.47	104.03	**−9.3**	−8.9	**−9.2**	−7.7
Sofia	41.00	38.54	42.60	23.40	−4.1	+0.4	−6.1	−1.1
Karaganda	40.31	43.60	49.80	73.08	**−4.7**	−8.1	−4.5	**−3.3**
Khabarovsk	37.91	40.19	48.52	135.12	**+3.6**	+9.3	+1.3	+7.9
Novokazalinsk	37.60	39.54	45.77	62.12	−5.9	−8.9	−5.9	−7.1
Alma_Ata	33.42	35.74	43.25	76.92	+6.5	**+12.1**	**+4.0**	+10.0
Tashkent	32.30	33.85	41.33	69.62	+5.8	**−1.6**	**+2.1**	**−1.1**
Ashkhabad	30.39	30.55	37.90	58.30	**−1.4**	**−4.4**	−3.5	**−5.4**
Akita	29.53	30.23	39.70	140.10	**−0.7**	**+0.2**	**−3.3**	**+0.4**

3 Geomagnetic control

Ground-based ionosonde observations at 30 European, North American and Asian stations are used in this study. The station list is given in Table 2. The selected stations are situated between 38°N and 81°N geographic latitude (30°N and 71°N geomagnetic latitude) and cover a broad longitudinal range, which provides a possibility to study spatial variations of the trend magnitude.

Regressions of δfoF2 with R_{12} (model 1) and with $R_{12} + Ap$ (model 2) are used to find the slope K (in 10^{-4} per year) of linear regression for each station, 12 and 00 SLT. Some examples of annual mean linear trends for daytime (12 LT) and nighttime (00 LT) hours are given in Fig. 1, years of solar minimum being used for the analysis. Seasonal (over 12 months) scatter in δfoF2 is shown in Fig. 1 as well. Median δfoF2 over these 12 values is found and this value is considered as the annual mean value used in further analysis.

Table 2 shows the results when years of solar maximum and minimum (Table 1) are analyzed together, while Table 3 gives the results on years of solar minimum and maximum separately. An F-test was applied to the annual mean slopes K to estimate the confidence level. Such annual mean K values may be considered as independent as they refer to different years and solar cycles. As the number of pairs N is rather small (5–14) and the scatter of individual points sometimes is rather large the confidence level may be less than 90%.

Figure 2 gives the latitudinal dependence for annual mean slopes K (model 1) for three selections of years, 12 and 00 SLT. Figure 3 shows results for the same conditions but for model 2. Only significant trends from Tables 2 and 3 are included in Figs. 2 and 3. The error bars present the standard deviation over 12 monthly slopes of K. High-latitude stations with positive nighttime trends (Tables 2 and 3) are not included in Figs. 2 and 3, these cases are discussed later. An analysis has shown that the invariant latitude (Table 2) usually provides better regression accuracy compared to regressions with geomagnetic or geodetic latitudes, so it was used in Figs. 2 and 3.

The trends revealed demonstrate a pronounced dependence on invariant latitude both for daytime and nighttime hours. Trends calculated over years of solar minimum (m) show a steeper latitudinal dependence and are more negative compared to ($M + m$) selection of years. In contrast, trends found over years of solar maximum (M) are more positive and are insignificant at the 90% confidence level at many stations (Table 3). We

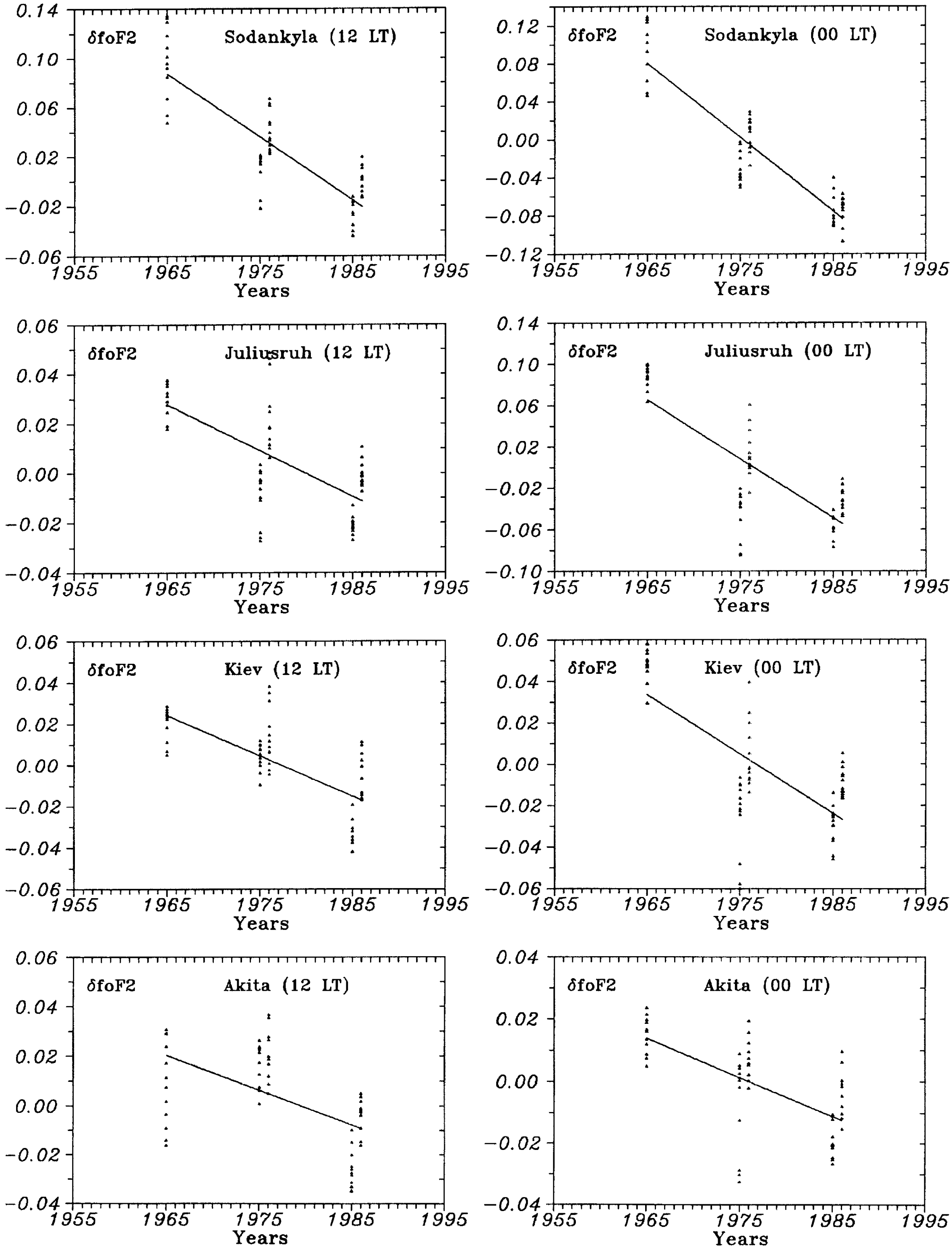

Fig. 1. Some examples of annual mean *f*oF2 trends for daytime and nighttime hours using only years of solar minimum. *Triangles* are individual monthly δfoF2 values

have used stations with observations available for three solar cycles, that is with three extrema for (M) and (m) year selections. Trends for stations with two available solar extrema were not considered although they may be significant according to the Fisher criterion.

Inclusion of the Ap index to the regression (model 2) makes the slopes K more positive in general and decreases the steepness of the latitudinal dependence for K. Sometimes it is even impossible to tell whether there is any latitudinal dependence for K, for instance,

Table 3. Calculated annual mean slope K (in 10^{-4} per year) for the period after 1965. Regressions of *f*oF2 with R_{12} (model 1) and with $R_{12} + Ap$ (model 2) are used to produce *f*oF2 trends for years of solar minimum and solar maximum. Bold face are significant trends with a confidence level ≥90%, normal face are trends which are not significant at the 90% confidence level

Station	12 SLT (M1)		00 SLT (M1)		12 SLT (M2)		00 SLT (M2)	
	Min ⊙	Max ⊙	Min ⊙	Max ⊙	Min ⊙	Max ⊙	Min ⊙	Max ⊙
Kheysa	**−58.6**	−13.7	−42.2	−22.7	**−48.9**	**−7.4**	**−31.8**	−16.3
Sodankyla	**−51.3**	**−74.2**	**−78.1**	+24.8	**−38.0**	**−62.5**	**−75.2**	−22.8
Dikson	**−37.0**	−14.6	−13.0	**−18.0**	**−29.3**	−8.2	−5.2	−11.6
Lycksele	**−33.1**	**−9.8**	−17.7	+28.3	**−23.7**	**−5.7**	−16.6	+28.2
Uppsala	**−33.9**	**−24.2**	**−58.9**	**−37.2**	**−27.4**	**−19.2**	−43.5	−24.9
Salekhard	**−33.9**	−17.5	+23.1	**−25.8**	**−27.1**	−11.5	+18.4	**+22.1**
Ottawa	**−27.1**	−10.6	−12.7	+12.3	**−24.6**	−5.8	**−1.2**	+19.3
Petersburg	**−27.3**	−10.9	−47.3	−3.0	**−21.7**	−5.8	−34.7	+6.1
Juliusruh	−18.6	−9.2	**−57.3**	−25.3	**−15.8**	−5.8	**−46.0**	−16.6
Slough	**−25.3**	+1.3	−38.7	**−2.2**	**−19.3**	+4.6	−29.7	**+4.5**
Dourbes	**−13.3**	+25.7	−22.0	**+29.9**	**−11.7**	**+26.9**	−12.7	**+33.1**
Kaliningrad	**−25.2**	**−4.3**	**−51.9**	−18.6	**−22.5**	**−1.7**	−38.9	−8.4
Yakutsk	**−43.4**	**−16.0**	**−67.6**	−13.9	**−35.4**	**−10.9**	**−52.4**	−5.2
Moscow	**−27.4**	**−5.6**	**−55.1**	−13.7	**−24.2**	−2.3	**−44.4**	**−4.9**
Gorky	**−25.9**	**−2.1**	**−66.2**	**+7.5**	**−22.4**	+0.1	**−58.6**	+12.5
Poitiers	−10.7	**+4.9**	**−24.2**	**−3.5**	−11.4	**+4.8**	**−20.0**	−0.3
Boulder	**−27.6**	**−0.3**	−10.8	+11.7	**−25.6**	**+1.4**	−10.0	+12.4
Ekaterinburg	−11.9	−10.9	−24.0	−30.2	−9.9	−8.2	**−17.5**	−23.7
Kiev	**−19.6**	+1.7	**−28.8**	**−5.0**	**−18.9**	+2.3	**−21.5**	+0.3
Tomsk	**−20.2**	+17.7	−32.0	−10.7	−19.4	+18.8	−26.7	**−6.2**
Rome	**−11.6**	+15.4	−17.2	**+4.8**	**−15.5**	+12.9	−18.8	**+3.3**
Irkutsk	**−17.8**	−6.4	−29.1	**−0.8**	**−18.0**	−6.1	−27.3	**+0.3**
Sofia	−13.7	**+2.9**	**+1.2**	**−0.3**	−16.1	+1.4	−1.4	−0.9
Karaganda	**−18.8**	+15.3	−19.2	**+11.1**	**−18.2**	+15.3	**−14.2**	+15.3
Khabarovsk	−5.03	+8.9	+11.7	+9.9	−8.7	+7.1	+10.0	+8.5
Novokazalinsk	**−17.4**	**+11.9**	**−20.9**	+11.9	**−17.1**	**+11.6**	**−19.2**	+13.5
Alma_Ata	+1.12	+9.2	**+0.3**	**17.1**	**−2.0**	+6.8	**−1.7**	15.0
Tashkent	**−4.20**	+11.1	**−0.6**	**−2.3**	−9.4	+7.8	**−0.05**	**−1.7**
Ashkhabad	**−5.40**	**+1.7**	−10.5	−0.9	−8.6	−0.1	−11.9	−1.7
Akita	**−14.0**	+14.2	**−12.5**	**+20.7**	−16.9	+13.3	**−12.5**	**+20.2**

with the (M) selection of years and 00 SLT (Fig. 3, right hand, bottom).

The main results of this analysis are the following:

1. The calculated significant trends are negative for the stations considered (especially for m selection of years) and demonstrate a pronounced latitudinal dependence with the slope K being more negative at higher invariant latitudes regardless the year selections and model used;

2. Trends calculated over the years of solar minimum are more negative and significant on more number of stations compared to the (M) selection of years. The (m) selection of years provides a more pronounced and steeper latitudinal dependence for the slope K. Therefore, we may conclude that the inclusion of (M) years to the trend analysis in fact contaminates the initial material although not to such extent as the years during falling and rising phases of solar cycle (Danilov and Mikhailov, 1998, 1999). Therefore, the ($M+m$) year selection may be used for *f*oF2 long-term trend analysis as the additional (M) years increase the statistics.

3. The revealed dependence of trends on invariant latitude clearly indicates a geomagnetic control and possible relationship with F2-layer storms (see later). An inclusion of the Ap index in the regression in fact does not remove the geomagnetic dependence as Bremer (1992, 1998) supposed but only contaminates the analyzed material increasing the scatter of points around the regression line. When model M2 is used, K depends on geomagnetic latitude as well. Therefore, further analysis is made only with model 1 as it provides purer results.

A well-pronounced dependence of *f*oF2 trends on latitude tells us that the effect may be related to the F2-layer storms due to the long-term increase of geomagnetic activity observed after 1965 (Fig. 4, top panel). Let us analyze the results obtained from this point of view. The main processes responsible for the F2-layer storm effects are known, they are neutral composition, temperature, and thermospheric wind changes at middle and lower latitudes while electric fields and particle precipitation strongly affect the high-latitude F2-region (see Prölss, 1995, and references therein). The magnitude of negative storm effects increases with latitude due to a noticeable decrease in O/N_2 ratio. In contrast positive storm effects dominate at lower latitudes and they are mostly due to the increase of the equatorward thermospheric wind (see Prölss, 1995; Mikhailov *et al.*, 1995 and references therein). Therefore, the observed dependence of trends on invariant latitude (Figs. 2, 3) may be just related to this F2-layer storm mechanism.

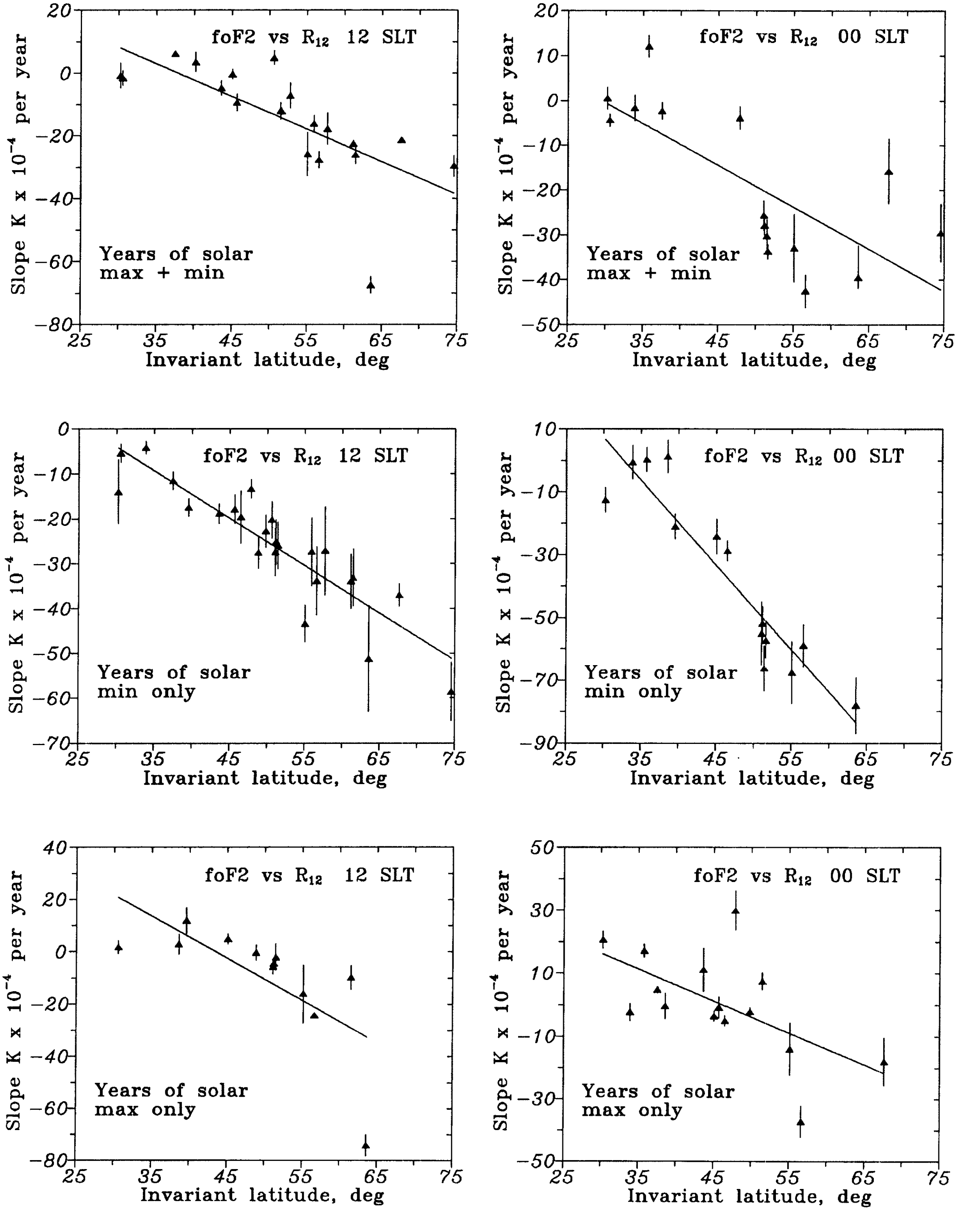

Fig. 2. Daytime and nighttime annual mean slope K at stations versus invariant latitude for the period with increasing geomagnetic activity 1965–1991. Model 1 (*f*oF2 versus R_{12} regression) and three year selections: $(M+m)$, (m) and (M) are used in the analysis (see text). Only stations with significant trends and a confidence level ≥90% are shown. Error bars present the standard deviation of seasonal (over 12 months) scatter of the slope K

An additional support of this concept provides the *f*oF2 long-term variation at Slough (Fig. 4) where observations are available from the early 1930s. Long-term variations of annual mean Ap_{12} and δfoF2 were analyzed for $(M+m)$ and (m) year selections. The least squares fitting by the 4th (higher degree gives practically the same result) degree polynomial shows the anti-phase type of δfoF2 and Ap_{12} long-term variations. As before error bars present the standard deviation over 12 monthly values. The periods of

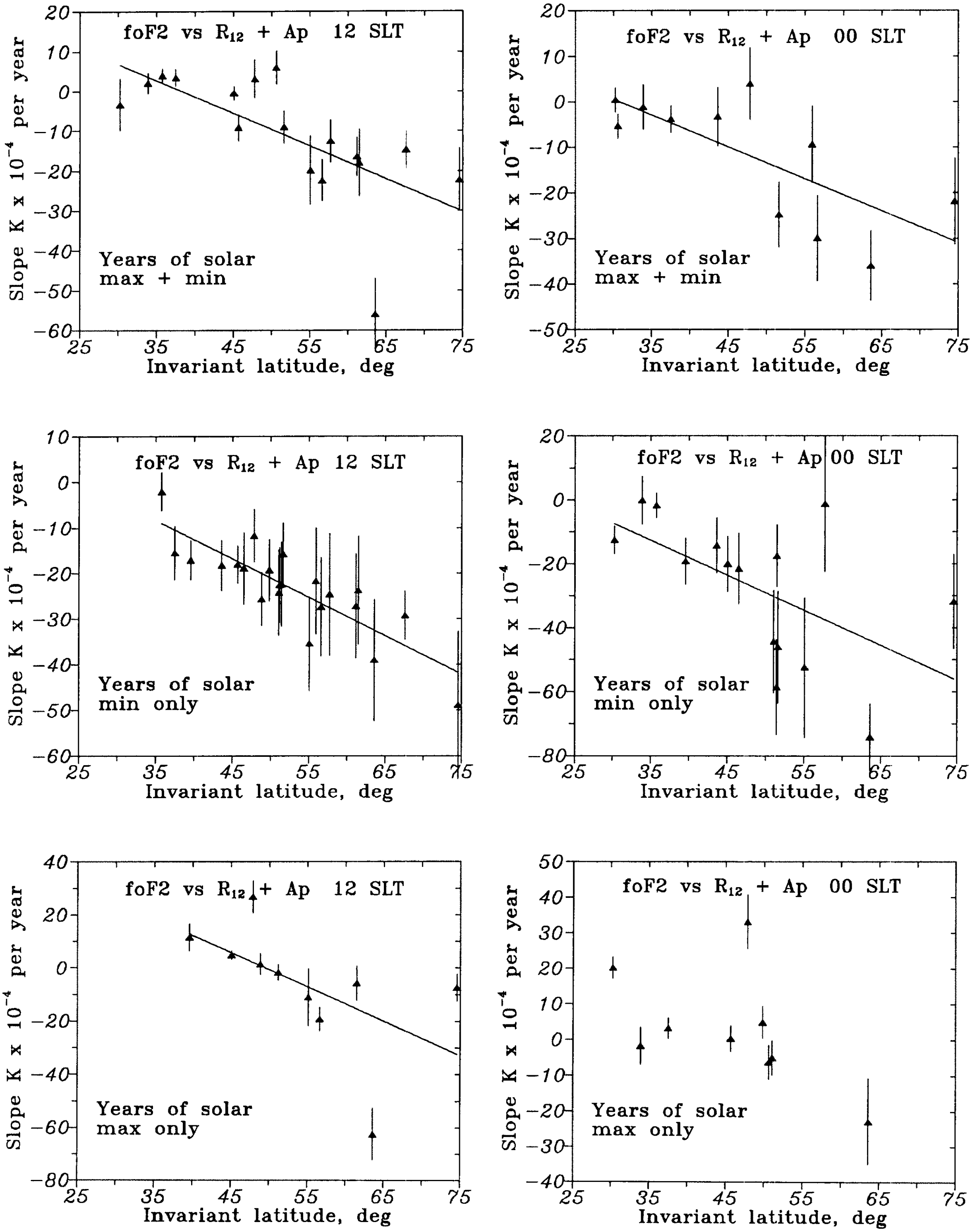

Fig. 3. Same as Fig. 1 but for model 2 (*f*oF2 versus R_{12} and *Ap* regression)

increasing geomagnetic activity (before 1945 and after 1965) are seen to correspond to negative *f*oF2 trends while during the decreasing geomagnetic activity (1945–1965) small positive trend takes place. There is also a tendency for the trend to switch from negative to positive after 1990 in accordance with the change in geomagnetic activity (Fig. 4, top). This dependence is more pronounced for the (*m*) selection of years (Fig. 4, dashes) in accordance with the discussed results. Although fitting curves give only a qualitative picture, the extrema in Ap_{12} variations take place earlier or coincide with the extrema in δfoF2 variations confirming the causal relationship between these parameters. Therefore, we may conclude that qualitatively *f*oF2 trends at Slough station just reflect the long-term variation in geomagnetic activity. An increase of

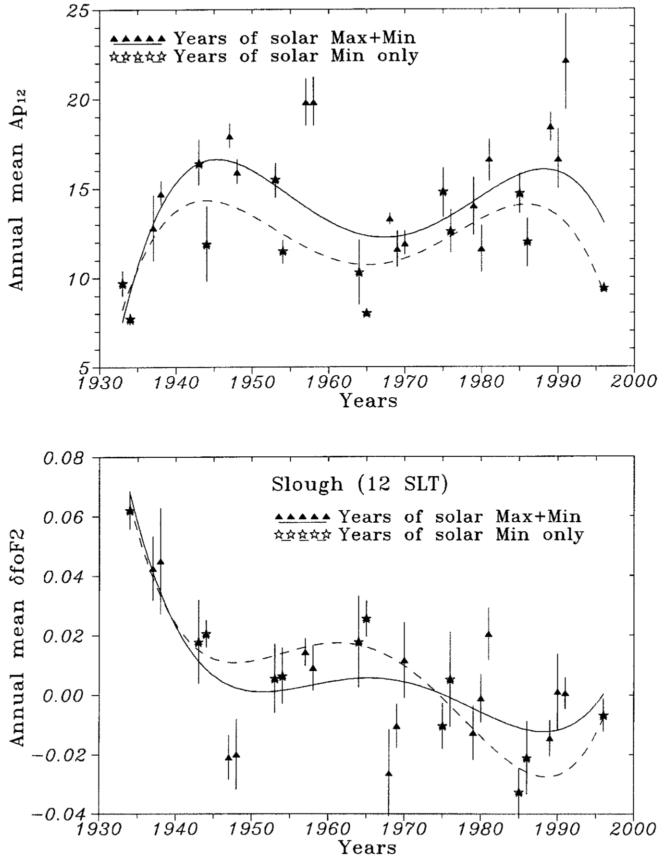

Fig. 4. Annual mean Ap_{12} and δfoF2 at Slough long-term variations. Two year selections ($M+m$) and (m) (see text) are used for the analysis. Least squares fitting curves are a 4th degree polynomials. Error bars present the standard deviation of the seasonal (over 12 months) scatter

geomagnetic activity results in negative *f*oF2 trends and vice versa.

To check this conclusion diurnal variation of the trends was analyzed for the periods before and after 1965 at Slough, Moscow and Tomsk stations (Fig. 5). These three midlatitude stations are separated in longitude to demonstrate global character of the analyzed effect. Two ($M+m$) year selections over similar time intervals were chosen: 1947–1965 (18 years) and 1975–1991 (16 years) to present the periods before and after 1965. The year 1965 is the turning-point in the long-term geomagnetic activity variation (Fig. 4. top) and if geomagnetic control of *f*oF2 trends does exist these trends should be different for the two periods. Positive annual mean trends for all LT moments take place for the period prior 1965 and negative trends after 1965 for the three stations considered. Error bars give a seasonal (over 12 months) scatter in the trends. All hourly *f*oF2 trends in Fig. 5 are significant at the confidence level ≥75%. Annual mean K values were used for the F-test. Although the confidence level is not high for some LT moments, the trends revealed demonstrate a consistent pattern of diurnal variation where individual K values seem not to be accidental.

Diurnal variations of *f*oF2 annual mean trends at different invariant latitudes also clearly indicate a close

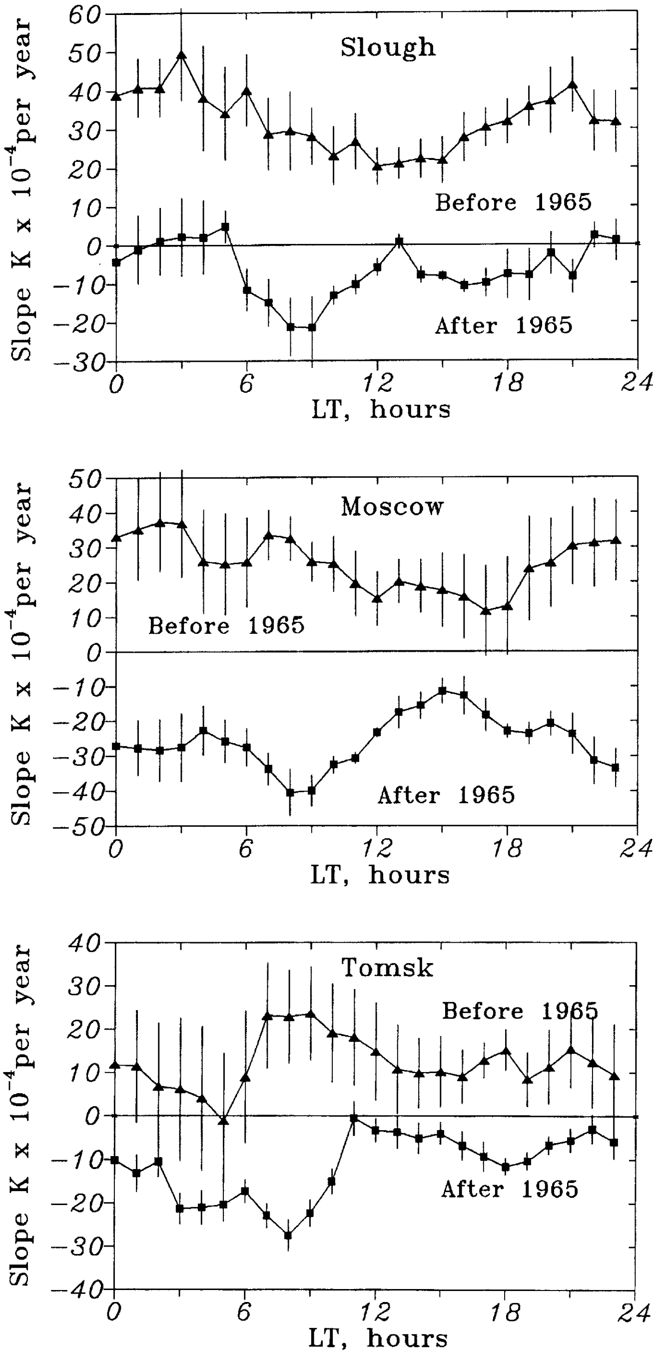

Fig. 5. Diurnal variation of annual mean slope K at three stations for the periods of decreasing (1947–1965) and increasing (1975–1991) geomagnetic activity. Note different signs of trends for the two periods. Error bars present the standard deviation of seasonal (over 12 months) scatter in the slope K

relationship of these trends with geomagnetic activity. Figure 6 gives diurnal variations of trends for: (1) a sub-auroral station, Salekhard, (2) St. Petersburg station located in the transitional (auroral/midlatitude) zone, (3) a midlatitude station, Ekaterinburg, and (4) a lower latitude station, Tashkent. The period after 1965 is considered with ($M+m$) selection of years. Salekhard station has strong positive trends for nighttime hours and strong negative trends during daytime. Ekaterinburg station demonstrates opposite behaviour with large negative nighttime trends and smaller trends during daytime hours. St. Petersburg shows mixed behaviour: the sub-auroral type for nighttime and midlatitude type during daytime hours. Low-latitude pattern of the trends is similar to the midlatitude one, but all values are more positive.

Let us consider a physical mechanism of these diurnal variations. Salekhard (Φ_{inv} = 61.18°) is located in the main ionospheric trough during nighttime hours (Muldrew, 1965; Karpachev *et al.*, 1996) next to the equatorial boundary of the diffusive precipitation zone with the increased ionization produced by soft electrons (see for references Besprozvannaya, 1986). The equatorial boundary of this zone is known to shift to lower latitudes by about 2° per one unity of *Kp* increase (e.g. Andrews and Thomas, 1969). Thus, strong positive night-time trends (Fig. 6) just result from an intensity increase of soft electron precipitation due to the overall increase in geomagnetic activity after 1965 and the shift of the precipitation zone to lower latitudes. During daytime hours the equatorial boundary of this zone is located far to the north at Φ_{inv} = 70–80° and we have strong negative *f*oF2 tends resulting from the disturbed neutral composition and electric fields (Prölss, 1980; Mikhailov and Schlegel, 1998).

Midlatitude trend diurnal variations (Ekaterinburg, Fig. 6) are due to disturbed neutral composition diurnal variations. Midlatitude negative F2-layer storm effects are known to be strongest in the post-midnight-early morning LT sector and they are much weaker in the afternoon (Wrenn *et al.*, 1987; Prölss, 1991, 1993, and references therein). This is due to the disturbed neutral composition with decreased O/N_2 ratio which is advected towards middle latitudes during night, rotates into

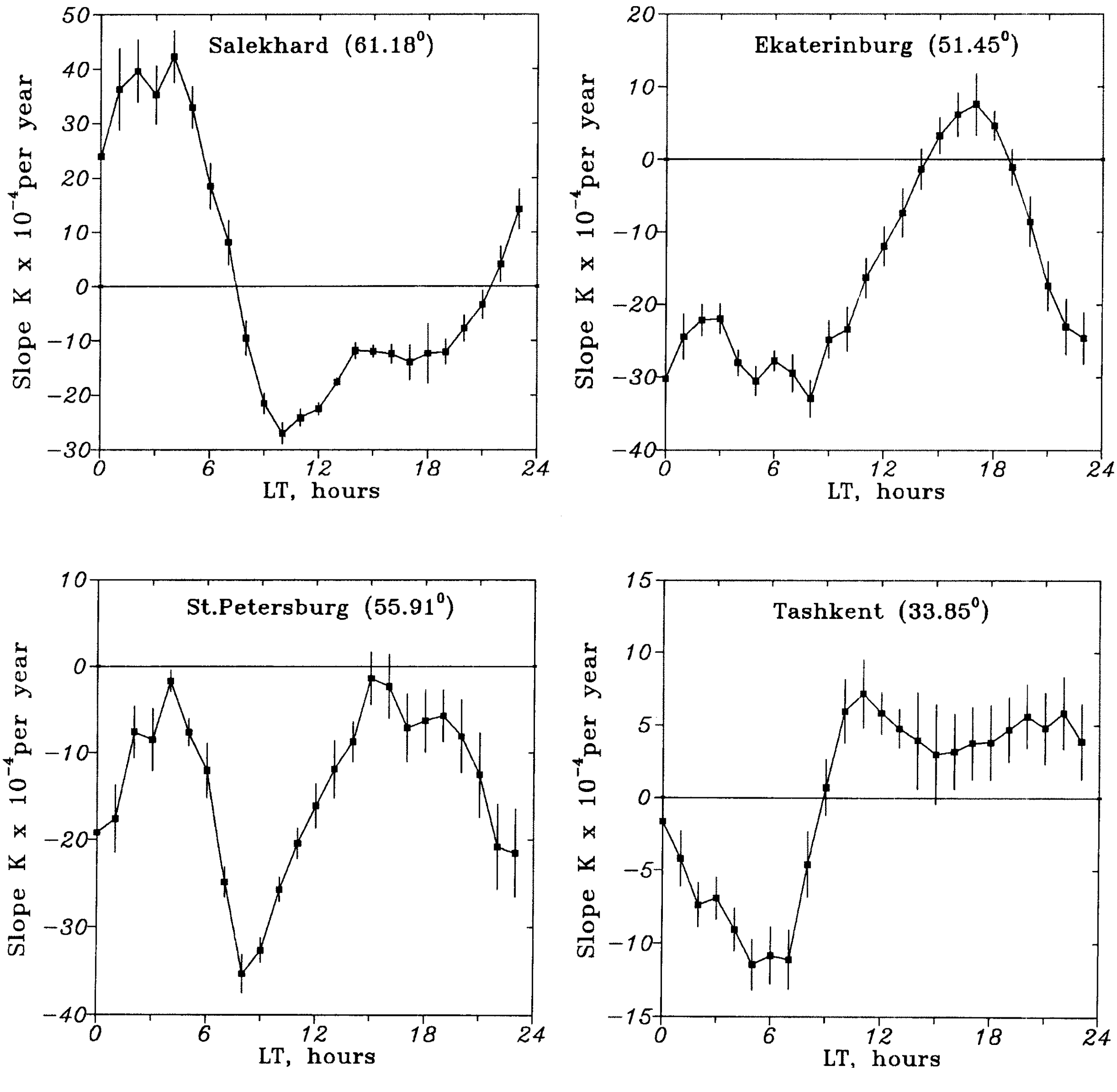

Fig. 6. Diurnal variation of annual mean slope *K* for stations located at different invariant latitudes (given in *brackets*). Note strong and opposite types of diurnal variations for sub-auroral and midlatitude stations. Error bars present the standard deviation of seasonal (over 12 months) scatter in the slope *K*

the day sector being shifted back to higher latitudes by diurnal varying thermospheric circulation (Skoblin and Förster, 1993; Fuller-Rowell *et al.*, 1994; Prölss, 1995). This effect is clearly seen for the afternoon hours with a tendency for trends to be even positive around 1500 LT.

St. Petersburg demonstrates the intermediate behaviour. In the 03–06 LT sector this station from time to time (depending on the level of geomagnetic activity) seems to be in the soft electrons precipitation zone like Salekhard and the trends are the least negative in this LT sector. On the other hand, the increasing geomagnetic activity after 1965 results in neutral composition and temperature perturbations and strong negative trends are seen in the morning LT sector. Negative trends are strongly decreased in the afternoon LT sector similar to the midlatitude station, Ekaterinburg.

As neutral composition perturbations decreases towards lower latitudes (e.g. Prölss, 1980) the magnitude of negative trends is small even in the morning LT sector at the lower latitude station, Tashkent (Fig. 6). During daytime hours the increasing geomagnetic activity damps normal northward thermospheric circulation leading to positive F2-layer storm effects (Prölss, 1995; Mikhailov *et al.*, 1995) and this results in positive *f*oF2 trends at lower latitudes (Fig. 6). The existence of strong and latitudinal dependent diurnal variations in the magnitude of the trends is a strong argument against any manmade e.g. greenhouse origin of these trends. But such variations may be explained in terms of the F2-layer storm effects related to the geomagnetic activity as was discussed earlier.

4 Discussion

A slightly modified method earlier proposed by Danilov and Mikhailov (1999) was applied to the *f*oF2 long-term trend analysis at 30 ionosonde stations. The slope K depends on latitude (Figs. 2, 3 and Tables 2, 3) with a pronounced decrease of the trend magnitude towards lower geomagnetic (invariant) latitudes for two models used in the analysis. Therefore, the proposed method of analysis with (m) or ($m+M$) selection of years allows us to find systematic variations in trend magnitude. Meantime the other approaches (e.g. Bremer, 1998; Upadhyay and Mahajan, 1998) result in a chaos of various signs and magnitudes of the trends on various stations.

One of the key points of the proposed method providing its success is the use of 12-month running mean *f*oF2 rather than just monthly medians. This strongly decreases the scatter in the analyzed material helping to reveal the trends. The application of an F-test to such smoothed observations to estimate the significance of the trends may be questionable as the filtered data turn out to be dependent to some extent. However, it should be stressed that we use annual mean δfoF2 values belonging either to different solar cycles or different years, that is separated by 12 months. This span equals the filtering running interval and our values turn out to be at the opposite ends of the smoothing interval, virtually not affecting each other. Therefore, such annual mean δfoF2 values may be considered as independent. Due to relatively small number of pairs analyzed, the confidence level is not high (about 75%) in some cases. But this is not important as the latitudinal and diurnal variations of the trends give, as a whole, a consistent picture showing the relationship to geomagnetic activity. On the other hand, one should keep in mind that all observed time series in geophysics and meteorology strictly speaking are never independent, nevertheless statistical methods are widely applied to such observations in practice (Panofsky and Brier, 1958). An example of the F-test application to the ionospheric trend analysis may be found in Bremer (1998). Estimating the significance of the trends he used hourly F2-layer parameter observations which are known to be strongly correlated.

The sunspot number R_{12} usually used in empirical ionospheric models is far from being the best (Mikhailov and Mikhailov, 1999) and in fact this index does not allow us to exclude completely the dependence on solar activity being used in *f*oF2 versus R_{12} regression. As the "useful signal" is very small in the trend analysis this imperfection of R_{12} results in scatter in analyzed points and various slopes K (both sign and magnitude) are obtained at various stations when all years are analyzed. The worst correlation of *f*oF2 with R_{12} takes place for the falling and rising phases of the solar cycles (the hysteresis effect), so these years were omitted from the analysis in the first place (Danilov and Mikhailov, 1998, 1999). The years around solar maximum are also subjected to this uncertainty, but to a less extent and their inclusion to the trend analysis allows us, nevertheless, to obtain a consistent pattern of trends over all stations considered. Of course, the best way for the *f*oF2 trend analysis would be not to use any reduction on solar activity with an index like R_{12}. Our analysis for years of solar minimum when the solar activity reduction is the minimal gives the most consistent results: all significant trends are negative with well-pronounced and steep dependence of K on invariant latitude (Table 3 and Figs. 2, 3). Acceptable results are obtained with the ($M+m$) selection of years as well. This tells us that the contaminating effect of the (M) years inclusion is not that strong. Indeed, a pronounced dependence of K on latitude takes place for (M) selection of years as well (Figs. 2, 3). Therefore, the ($M+m$) year selection may be recommended for the *f*oF2 trend analysis as was proposed earlier by (Danilov and Mikhailov, 1998, 1999). An inclusion of (M) years may be important as well for stations where the period of observation is not long enough to work with (m) years only. For instance, we used the ($M+m$) selection of years in Fig. 5 to increase the number of points for the period before 1965.

Although there is an obvious relationship of *f*oF2 trends with geomagnetic activity, the monthly Ap index is not a proper indicator for the F2-layer storm effects and its inclusion to the regression (model 2), in fact, does not remove the dependence on geomagnetic activity as supposed by Bremer (1998) and Jarvis *et al.*

(1998). Indeed, a well-pronounced dependence of K on latitude takes place for model M2 as well (Fig. 3) with the decreased trend magnitudes only. Thus, we may conclude that the inclusion of *Ap* indices to the regression excludes the geomagnetic effect only partly without changing, in principle, the dependence of trends on geomagnetic (invariant) latitude. Moreover, the inclusion of *Ap* indices to the regression (model M2) inserts additional noise to the analyzed material increasing the scatter of points around the regression line (see Figs. 2 and 3, left hand columns). This is not surprising as the global *Ap* index cannot, in principle, take into account the whole complexity of F2-layer storm effects with positive and negative phases depending on season, UT and LT of storm onset, storm magnitude etc. Thus, the *Ap* index inclusion cannot be recommended for the F2-layer trend analysis.

It should be stressed that our conclusions contradict those in the recent publication by Bremer (1998). He found no latitudinal effect in the trends, but revealed a separation of the stations to two longitudinal groups with positive trends in Eastern Europe and negative ones in Western Europe. We found no such longitudinal effect as most of the revealed trends are negative regardless of longitude, but there is a well-pronounced latitudinal dependence. We believe that the reason for the contradiction with the results of Bremer (1998) lies in the differences of approach. Bremer (1998) used absolute deviations from some model and all the years available for a given station. In this case the length of the data series used is inevitably quite different depending on the duration of the vertical sounding observations at this particular ionosonde. However, the sign of trends is different for the period prior to and after 1965, as follows from Fig. 5. This was the reason to separate these periods in our analysis. Further, Bremer (1998) analyzed annual trends averaging hourly and monthly values, but *f*oF2 trends demonstrate strong diurnal variations as was shown earlier (Figs. 5, 6) and this inevitably will decrease the reliability of the trends revealed.

The proposed F2-layer storm induced mechanism for the *f*oF2 long-term trends implies corresponding trends in *hm*F2. For the period with increasing geomagnetic activity and negative *f*oF2 trends, as we have after 1965, one should expect positive *hm*F2 trends at middle and lower latitudes. The trends should be inverse for the period with decreasing geomagnetic activity. This follows from a well-known F2-layer negative storm mechanism related to neutral composition and temperature changes (e.g. Prölss, 1995). Unfortunately, *hm*F2 trends inferred from $M(3000)$F2 are not as reliable as *f*oF2 trends, nevertheless such analysis is being done and results will be published elsewhere. It is worth mentioning that there are indications of some long-term trends in the occurrence frequency of ionospheric storms (Sergeenko and Kuleshova, 1995; Sergeenko and Givishvili, 1997; Clilverd *et al*., 1998). This is in line with the proposed concept on the *f*oF2 trends mechanism.

Total cooling of the upper atmosphere due to the greenhouse effect and related negative trend in *hm*F2 is discussed in some publications (e.g. Bremer, 1992; Ulich and Turunen, 1997). However, it may be shown that thermospheric temperature decrease would result in a positive trend in *f*oF2 contrary to the observations. According to the isobaric F2-layer concept by Rishbeth and Edwards (1989, 1990) the F2-layer peak follows, in its variations, the level of constant atmospheric pressure. This is a good approximation, at least during daytime hours, when vertical plasma drifts are not strong. Electron concentration NmF2 for a steady-state daytime midlatitude F2-layer is given by the expression of Rishbeth and Barron (1960):

$$N_m = 0.75\frac{q_m}{\beta_m} \tag{3}$$

where q_m and β_m are given at the F2-layer maximum. For estimates it may be assumed that $q \propto [\mathrm{O}]$ and $\beta \propto T^2 [\mathrm{N_2}]$. Then we may write using Eq (3)

$$\Delta \log\ N_m = \Delta\ \log\frac{[\mathrm{O}]_m}{[\mathrm{N_2}]_m} - 2\Delta \log T\ . \tag{4}$$

If [O] and $[\mathrm{N_2}]$ (molecular mass m_1 and m_2) are distributed in accordance with the barometric law

$$n = \frac{n_0 T_0}{T}\exp\left\{-\int_{h_0}^{h}\frac{\mathrm{d}h}{H}\right\} \tag{5}$$

where $H = kT/\mathrm{mg}$ and n_0 and T_0 are the concentration and temperature at the base height h_0, the pressure and $R = [\mathrm{N_2}]/[\mathrm{O}]$ at any height are related by the expression

$$P = kT_0\frac{n_{10}^{\frac{m_2}{m_2-m_1}}}{n_{20}^{\frac{m_1}{m_2-m_1}}}R^{\frac{m_1}{m_2-m_1}}(1+R)\ . \tag{6}$$

It follows from Eq. (6) that the ratio R remains constant at any fixed value of pressure P and at any temperature height profile provided T_0, n_{10} and n_{20} are constant. This is valid for any height and for *hm*F2 as well, so the first term in Eq. (4) equals zero. Therefore, the expected temperature decrease due to the greenhouse effect should result in a positive NmF2 trend as follows from Eq. (4), thus contradicting the observed negative NmF2 trends. This dependence on temperature is due to the $(\mathrm{O^+} + \mathrm{N_2})$ reaction rate constant temperature dependence. A steep quadratic dependence for this rate constant on T follows from the McFarland *et al.* (1973) laboratory measurements. Recent observations by Hierl *et al.* (1997) give weaker temperature dependence, but in any case this rate constant increases with temperature for usual ionospheric temperatures.

5 Conclusions

The main results of our analysis may be listed as follows:

1. A slightly modified version of a method proposed earlier by Danilov and Mikhailov (1999) was applied to

the *f*oF2 long-term trends analysis on 30 mid- and high-latitude ionosondes of the Northern Hemisphere. Years of solar minimum (m), maximum (M) and ($M+m$) were analyzed separately. Trends for 12 and 00 LT calculated over the (m) years were shown to be more negative and significant at a greater number of stations compared to the (M) selection of years. The inclusion of (M) years to the trend analysis in fact contaminates the initial material although not to such extent as the years of falling and rising phases of the solar cycle (Danilov and Mikhailov, 1998, 1999). The ($M+m$) year selection provides an acceptable result and may be recommended for *f*oF2 long-term trend analysis. The present analysis confirms our previous result on the dependence of the *f*oF2 trends on geomagnetic (invariant) latitude with strong negative trends at high and small or positive trends at lower latitudes for the period analyzed 1965–1991.

2. The revealed dependence of the *f*oF2 trends on invariant latitude clearly indicates the geomagnetic control and relationship with F2-layer storm mechanisms. An inclusion of the Ap index to the regression does not remove the geomagnetic dependence as proposed in some publications, but only contaminates the analyzed material without changing the result obtained in principle.

3. It is shown, for the first time, that there exist periods with negative and positive *f*oF2 trends, which correspond to the periods of long-term increasing/decreasing geomagnetic activity. The ($M+m$) analysis at Slough station for instance, gives the periods with negative *f*oF2 trends: 1934–1948, 1967–1989 and periods with positive trends: 1950–1968, and after 1989 in accordance with the smoothed variation of annual mean Ap_{12} index used as an indicator of geomagnetic activity. Different signs of the trends during the periods of increasing/decreasing geomagnetic activity take place for all LT moments at each individual station considered.

4. Strong diurnal variations in the trend magnitude are revealed for stations located at different latitudes. Strong positive *f*oF2 trends in the post-midnight-early morning LT sector and strong negative trends during daytime hours take place for the sub-auroral stations for the period of increasing geomagnetic activity after 1965. In contrast middle and lower latitude stations demonstrate negative trends in the early morning LT sector and small negative or positive trends during daytime hours for the same period. The existence of such diurnal variations in the *f*oF2 trend magnitude is a strong argument against any manmade (e.g. greenhouse) origin of such trends.

5. All the morphological features revealed of the *f*oF2 trends may be explained in the framework of contemporary F2-region storm mechanisms. They include disturbed neutral composition, temperature and thermospheric winds variation (for middle and lower latitude stations) as well as soft electron precipitation for sub-auroral stations. This newly proposed geomagnetic storm concept to explain the *f*oF2 long-term trends proceeds from a natural origin of the trends rather than an artificial one related to the thermosphere cooling due to the greenhouse effect.

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